Separation Methods Based on Distributions in Discrete Stages (02/02/15)

1. Chemical Separations: The Big Picture

   Classification and comparison of methods

2. Fundamentals of Distribution Separations

3. Separation Methods Based on Distributions in Discrete Stages

   Such as solvent extraction and distillation

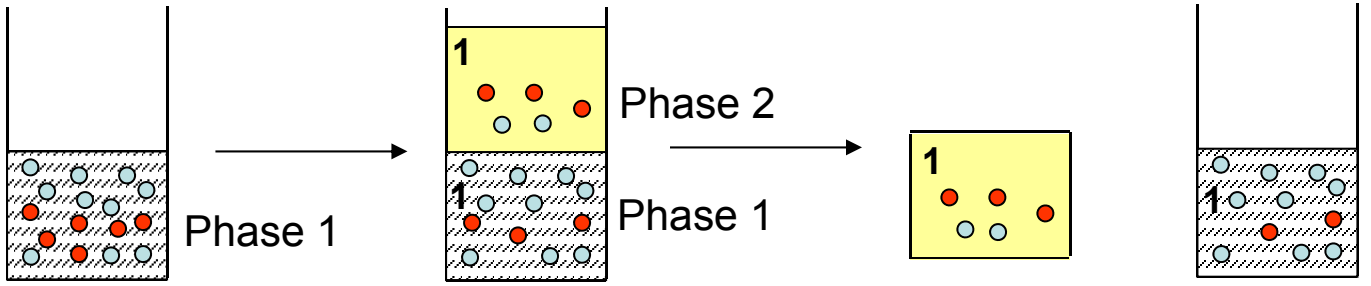
4. Introduction to Distribution Separations in chromatographic methods. The plate theory, the rate theory; van Deemter's equation.

Counter-Current Extraction

- [A] = 0.01 M
- [B] = 1 M

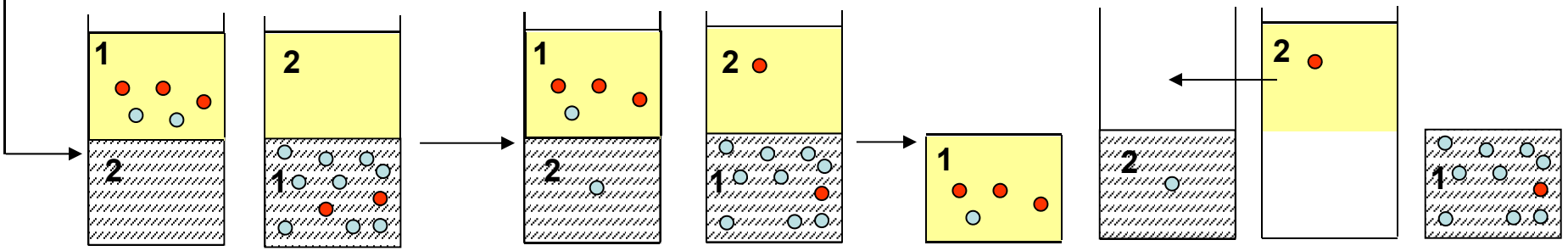
$V_1=V_2=10$ mL

$D_{cA}= 10$, $D_{cB}=0.1$



Extraction 1

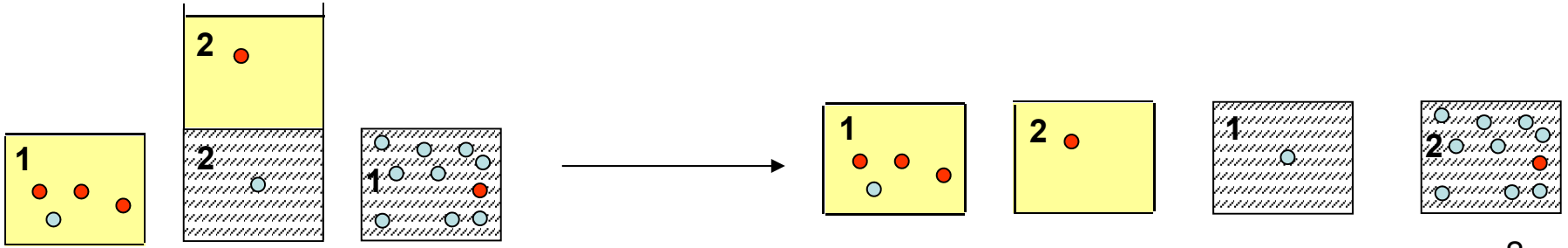
Separation of phases



Addition of fresh phases to Both phase 1 and 2

Extraction 2

Separation of phases



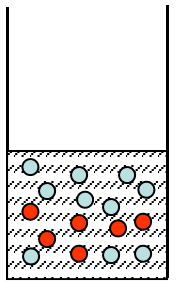
Extraction 3

Counter-Current Extraction

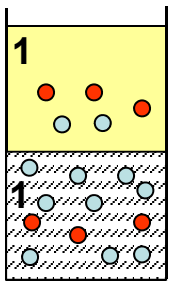
- [A] = 0.01 M
- [B] = 1 M

$V_1=V_2=10$ mL

$D_{cA}= 10$, $D_{cB}=0.1$



Phase 1



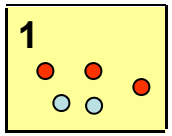
Phase 2

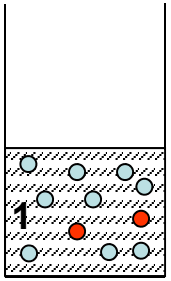
Phase 1

Extraction 1

$f_{A2,1}=0.909$

$f_{B2,1}=0.091$

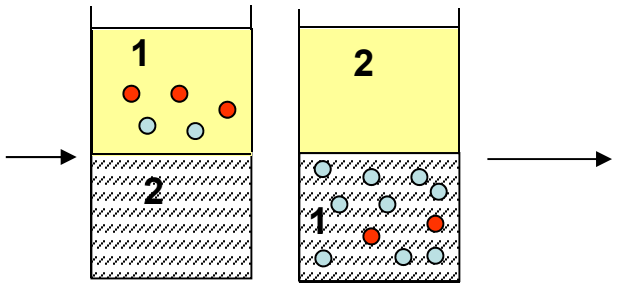




$f_{A1,1}=0.091$

$f_{B1,1}=0.909$

Separation of phases



Addition of fresh phases to Both phase 1 and 2

Total A =0.909

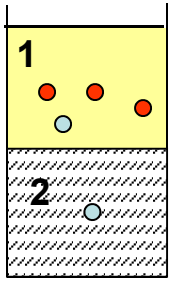
Total B =0.091

$f_{A2,2}=0.826$

$f_{B2,2}=0.008$

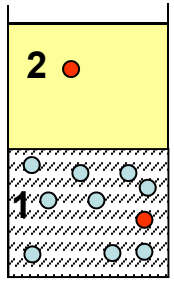
$f_{A1N,2}=0.083$

$f_{B1N,2}=0.083$



Total A = 0.091

Total B = 0.909



$f_{A2N,2}=0.083$

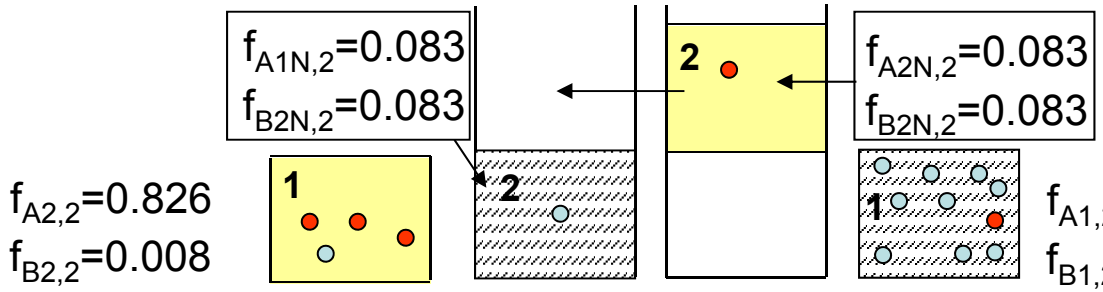
$f_{B2N,2}=0.083$

$f_{A1,2}=0.008$

$f_{B1,2}=0.826$

Extraction 2

Counter-Current Extraction



- [A] = 0.01 M
- [B] = 1 M

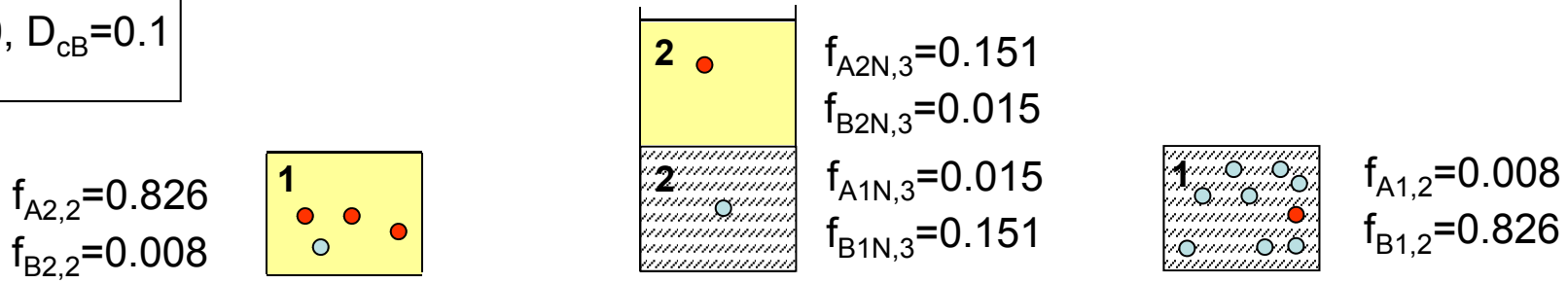
$V_1=V_2=10$ mL

$D_{cA}= 10$, $D_{cB}=0.1$

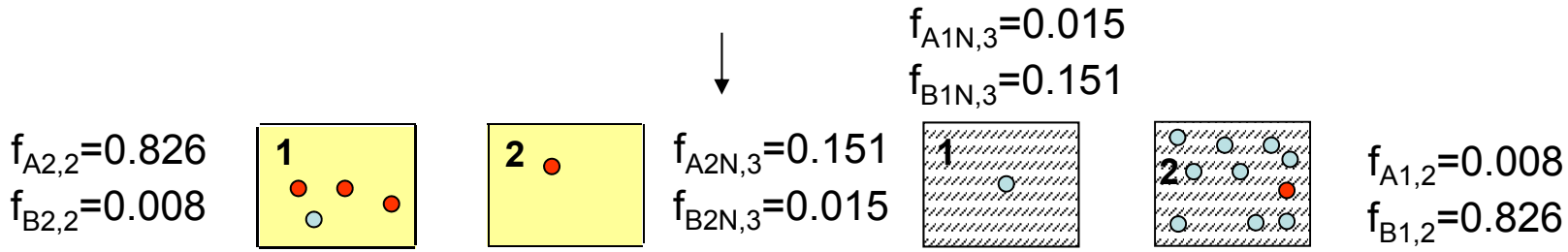
Separation of phases

Total A =0.166

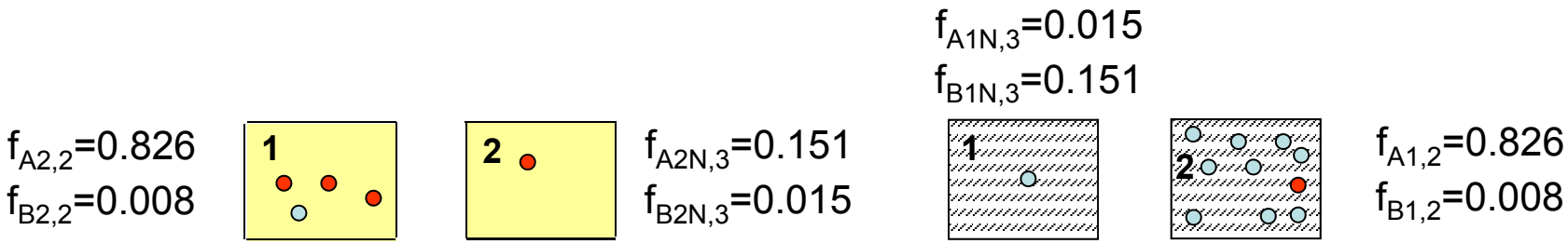
Total B =0.166



Extraction 3



Counter-Current Extraction



Results: recovery of A in phase 2 = 0.826+0.151=0.977=97.7%

$$\text{Final purity of A in phase 2} = \frac{(0.01M)*(0.01L)*(0.977)}{(0.01M)*(0.01L)*(0.977) + (1.00\ M)*(0.01L)*(0.023)} = 0.298=29.8\%$$

$$\text{Purification yield} = \frac{0.298}{0.0099} = 30$$

	One-step	Two-step	Counter-current
Recovery of A in phase 2 = 0.909 = 90.9%		99.2%	97.7%
Final purity of A in phase 2 = 0.091 (9.1%)		5.4%	29.8%
Purification yield of A =	9.2	5.45	30

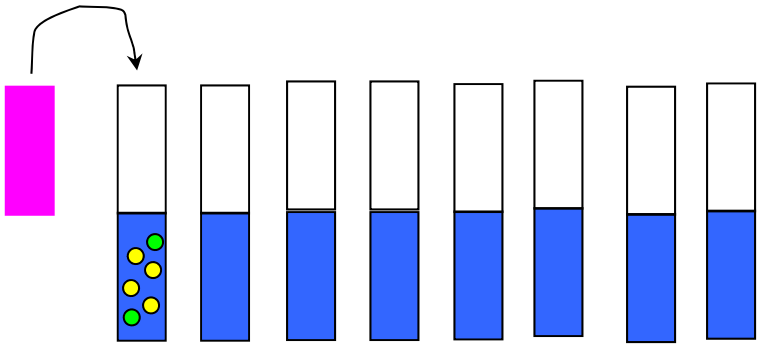
F. Craig Apparatus and Craig Countercurrent distribution

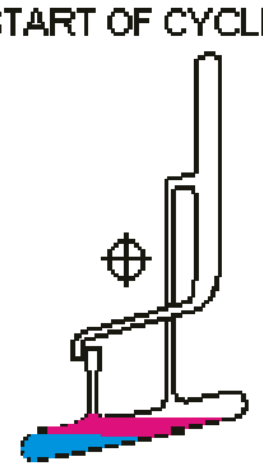
(1) Counter-current extraction are useful in that they improve both the recovery and purification yield of A. However, the technique is time-consuming and tedious to perform.

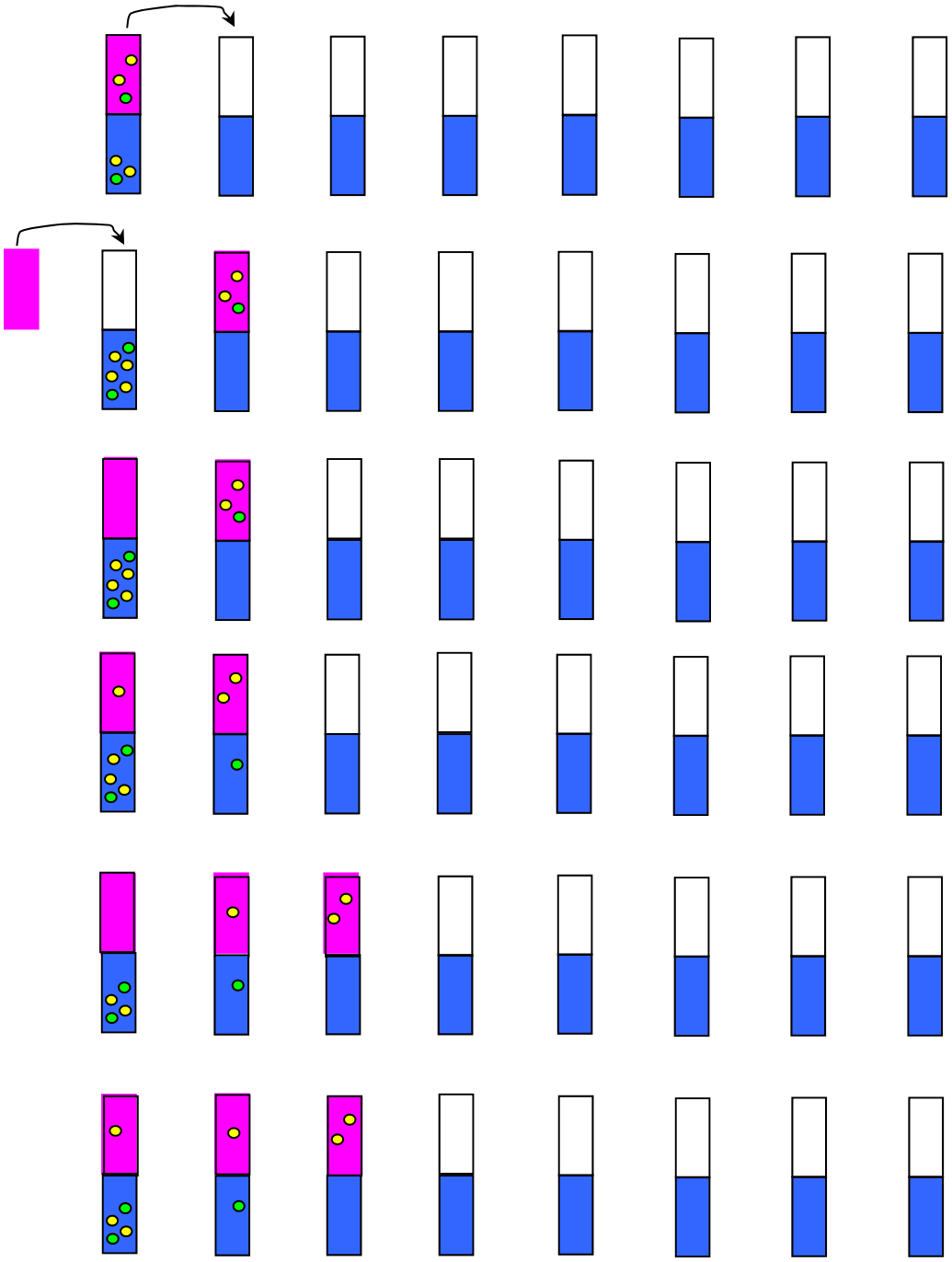
(2) To overcome these difficulties L. C. Craig developed a device in 1994 to automate this method. Known as the Craig Apparatus, this device uses a series of "separatory funnels" to perform a counter-current extraction. The patern formed by the movement of a solute through the system is known as a counter-current distribution.

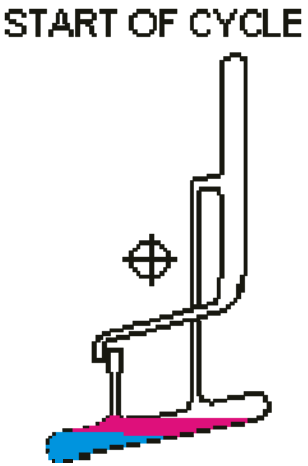
Lyman C. Craig, Ph.D.

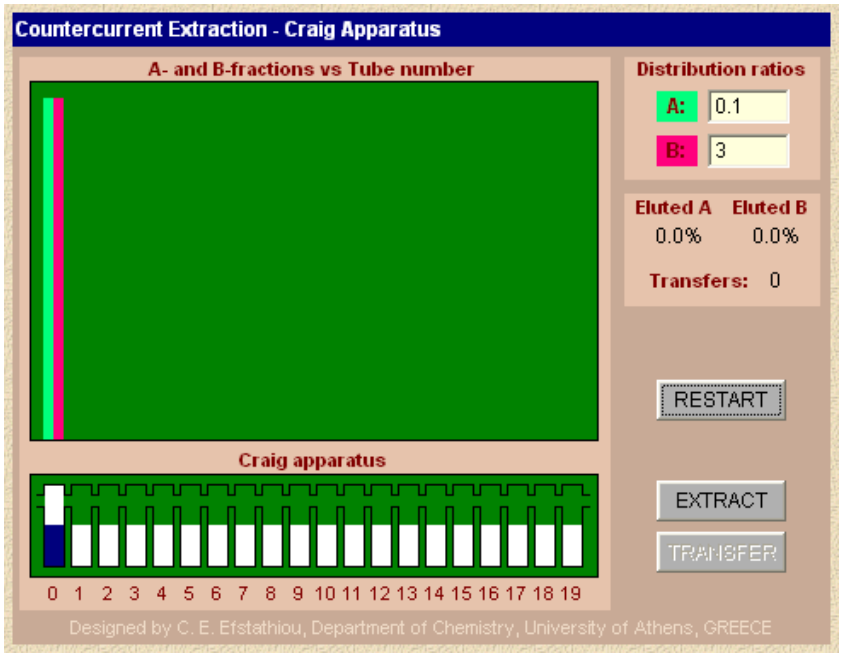
Albert Lasker Award

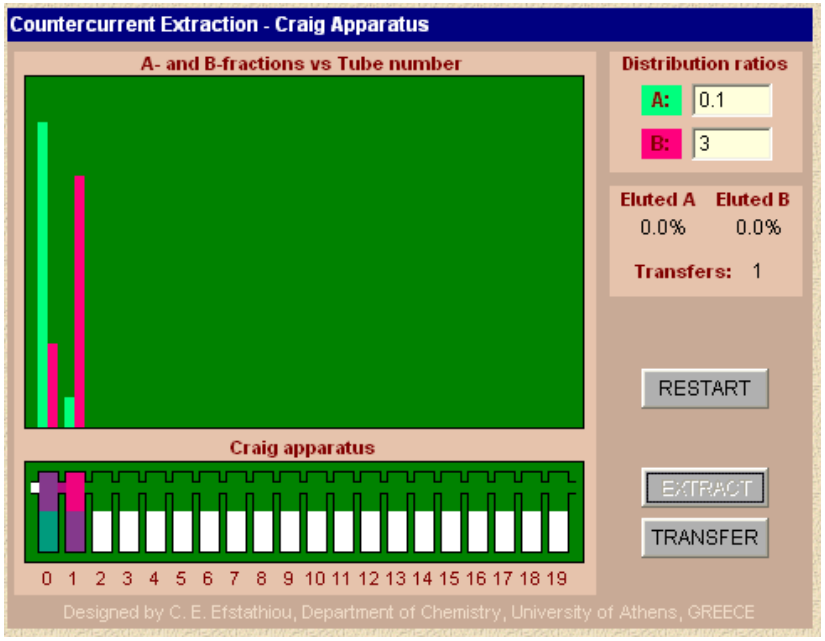


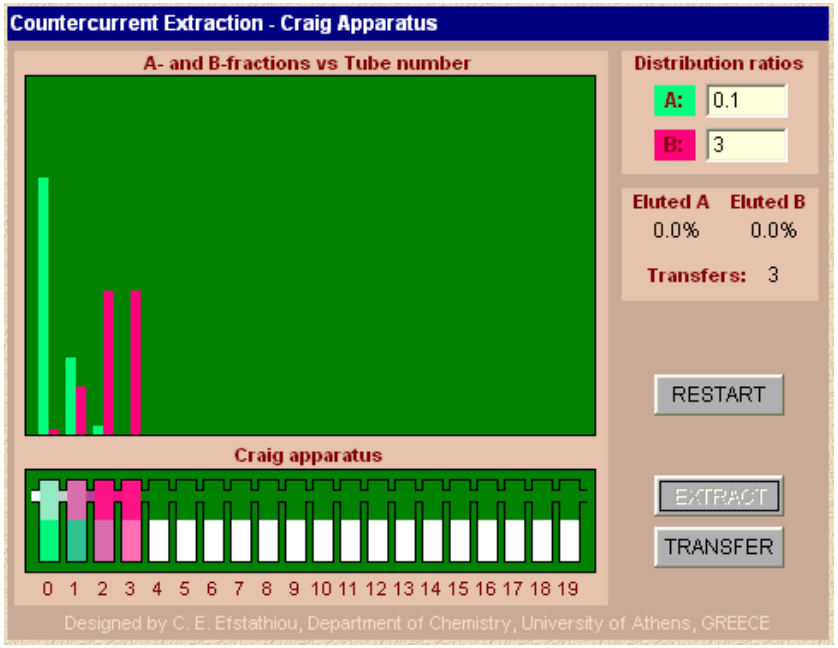


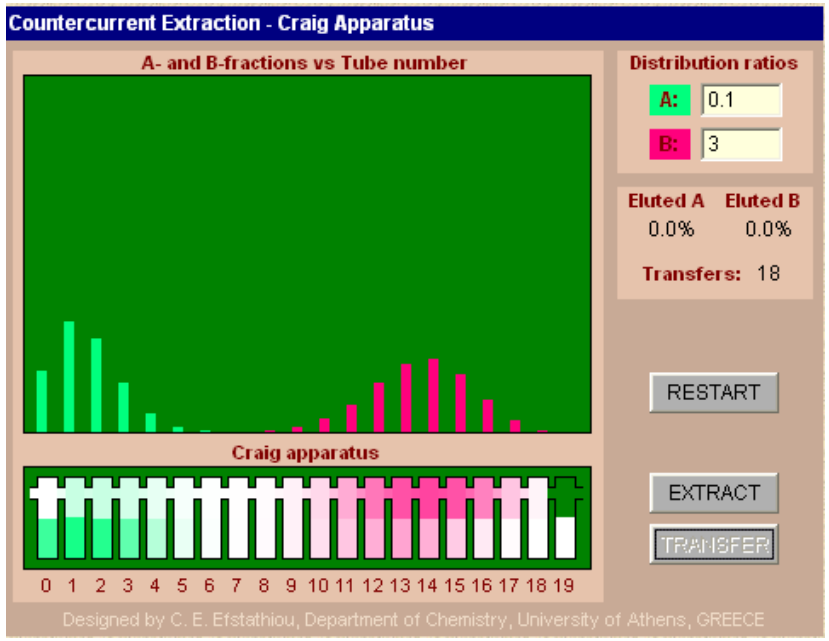

Extraction 1
Transfer 1a
Transfer 1b
Extraction 2
Transfer 2
Extraction 3


START OF CYCLE





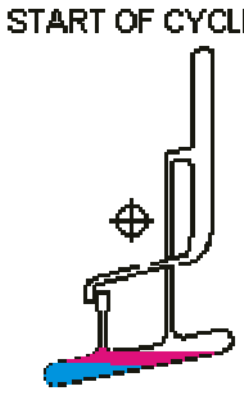




http://www.chem.uoa.gr/Applets/AppletCraig/Appl_Craig2.html

(4) The result of this process is that solutes partition between the phases in each tube, but eventually all travel to the right and off of the apparatus, where they are collected.

(5) Since this system involves both rate and phase separation processes (i.e., distribution of solutions between two phases affecting their rate of travel through the system), The Craig countercurrent distribution is often as a simple model to describe chromatography. In fact, anther term often used for countercurrent distribution is countercurrent chromatography (CCC).



The Essence of Chromatography: p889 ~ 893

H. Theory of Countercurrent distribution:

(1) As in simple extraction, the distribution of A in any tube can be calculated based on it concentration distribution ratio, where

$$f_{phase1} = \frac{1}{(1 + D_c\, V_2/V_1)}$$ (fraction of A not removed from phase 1)

$$f_{phase2} = 1 - f_{phase1,1}$$ (fraction of A extracted into phase 2)

(2) In describing the Craig distribution, the terms fphase1 and fphase2 are often replaced with the terms **q** and **p**, where

$$\mathbf{q} = f_{phase1} = \frac{1}{(1 + D_c\, V_2/V_1)}$$

$$\mathbf{p} = f_{phase2} = 1 - f_{phase1,1} = 1 - \mathbf{q}$$

(3) The ratio of q/p (i.e., the ration of the fraction (or moles) of A in the stationary phase to the faction (or moles) of A in the mobile phase at equilibrium) is known as the capacity factor k.

$$k' = p/q$$

$$= \text{mole } A_{\text{mobile phase}}/\text{moles } A_{\text{stationary phase}}$$

(4) The equation for $k = q/p$ may also be rewritten in terms of p and q, where

$$p = k'/(1 + k')$$

$$q = 1/(1+k')$$

(5) k and concentration distribution ratio (D_c) are related by the expression

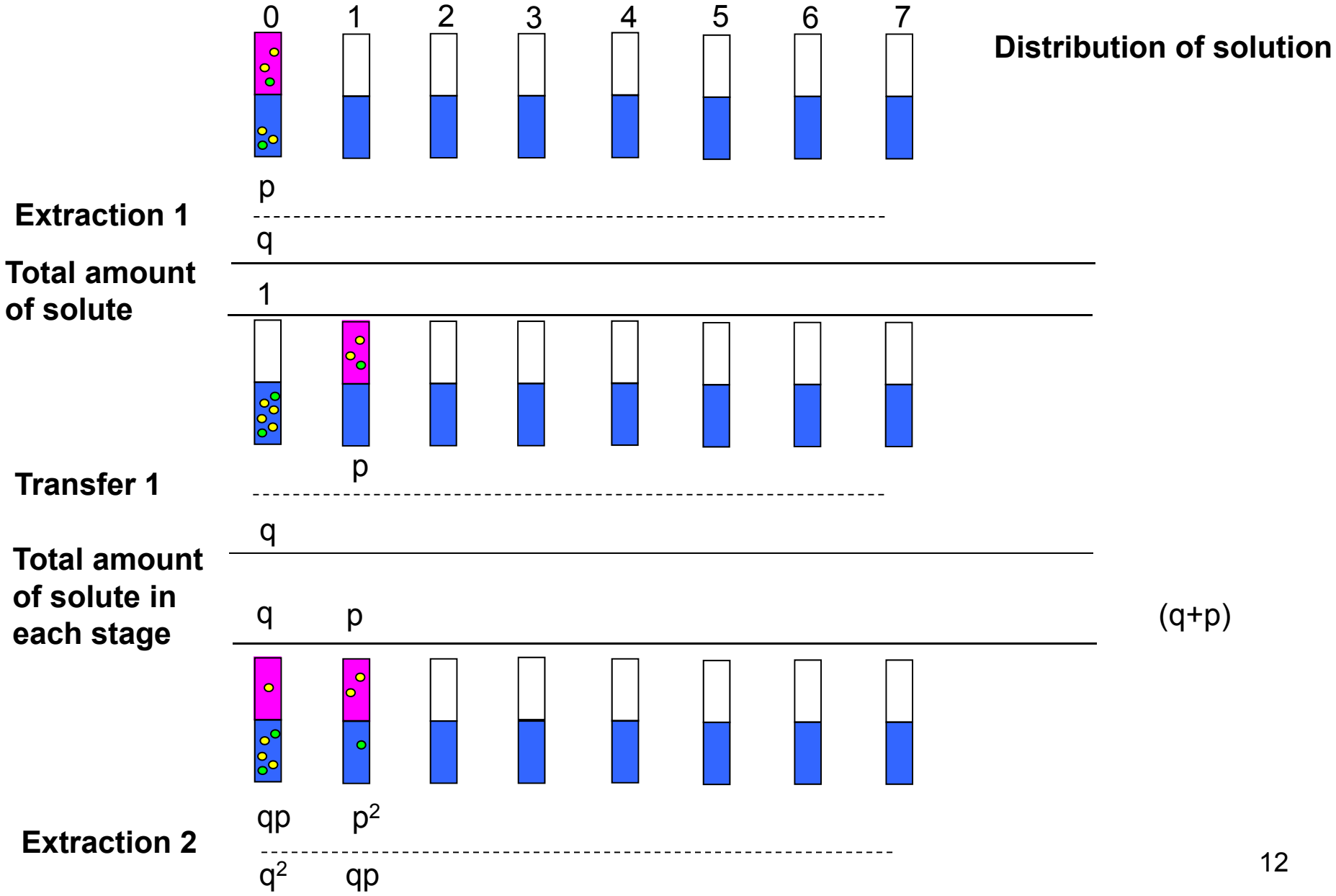
$$k' = D_c V_2/V_1$$

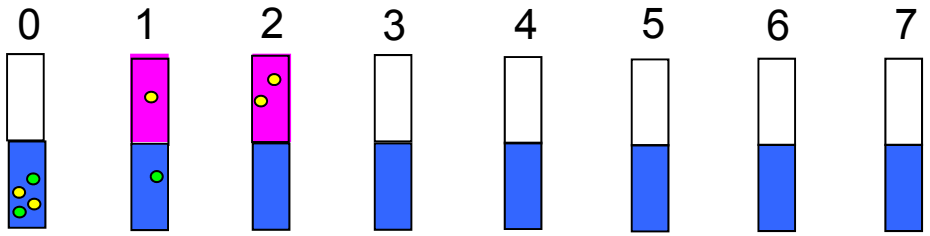
In other works, k' is another way to describe the distribution of A between two phase. D_c and k only differ in that k is based on the moles of A present rather than its concentration. For this reason, k' is sometimes referred to as the mass distribution ratio.

(6) The use of k' to describe the distribution of a solute is particularly valuable in situations where the exact volumes of the mobile and stationary phases are not known. One common example of this is on chromatography ($k=1/k'$).

(7) The value of k', or p and q, can also be used to describe the distribution of a solute A in the Craig apparatus.

Development of solute distribution in Craig Apparatus





Distribution of solution

Transfer 2

qp p^2

q^2 qp

Total amount of solute in each stage

q^2 $2qp$ p^2 $(q+p)^2$

Extraction 3

q^2p $2qp^2$ p^3

q^3 $2q^2p$ qp^2

Transfer 3

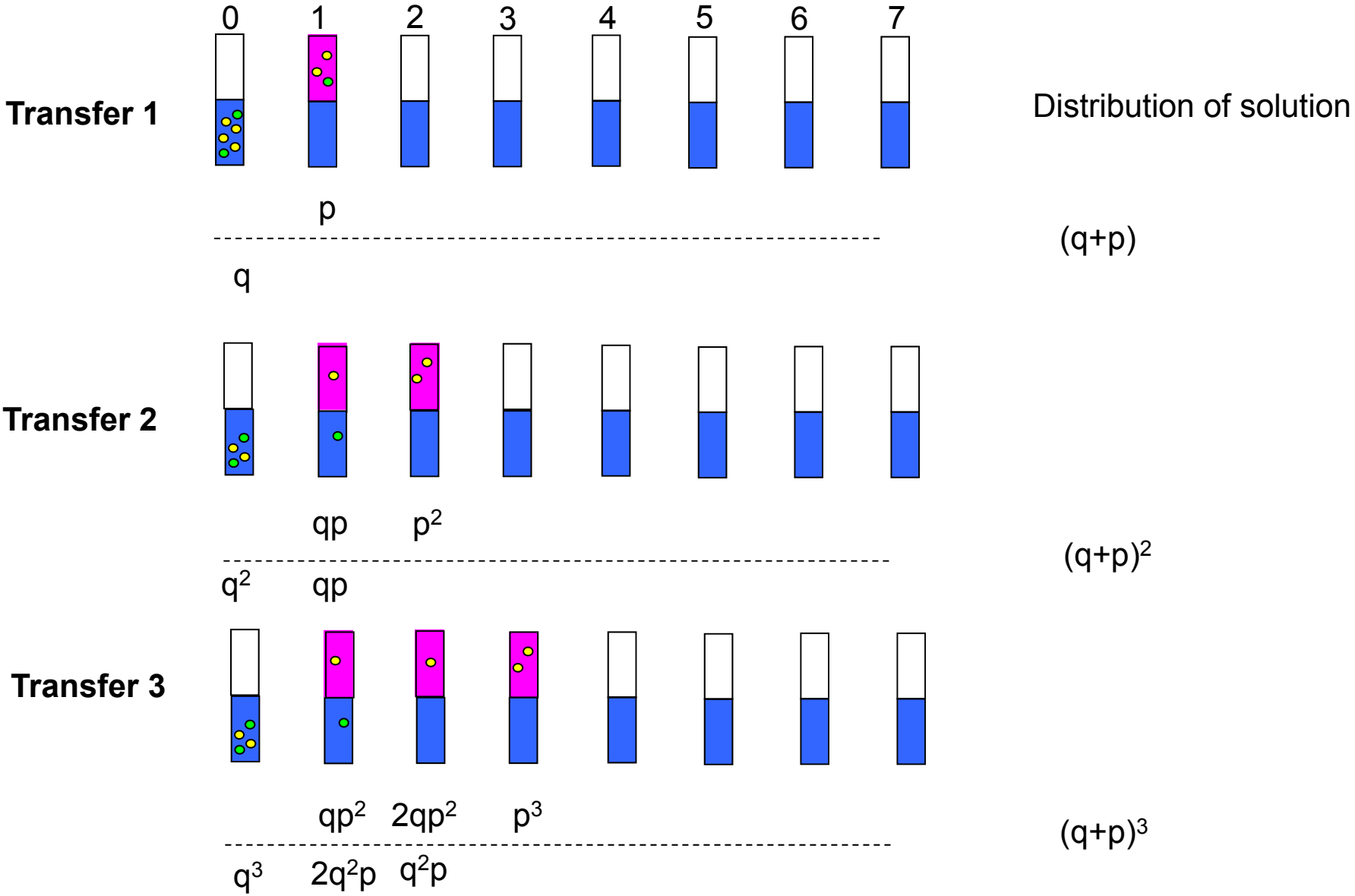
q^2p $2qp^2$ p^3

q^3 $2q^2p$ qp^2

Total amount of solute in each stage

q^3 $3q^2p$ $3q^2p$ p^3 $(q+p)^3$

Development of solute distribution in Craig Apparatus



(8) The distribution of A in this system after r transfers is given by the binomial expression of the equation

$$(q + p)^r = 1$$

Where: $(q+p)^1 = q + p$

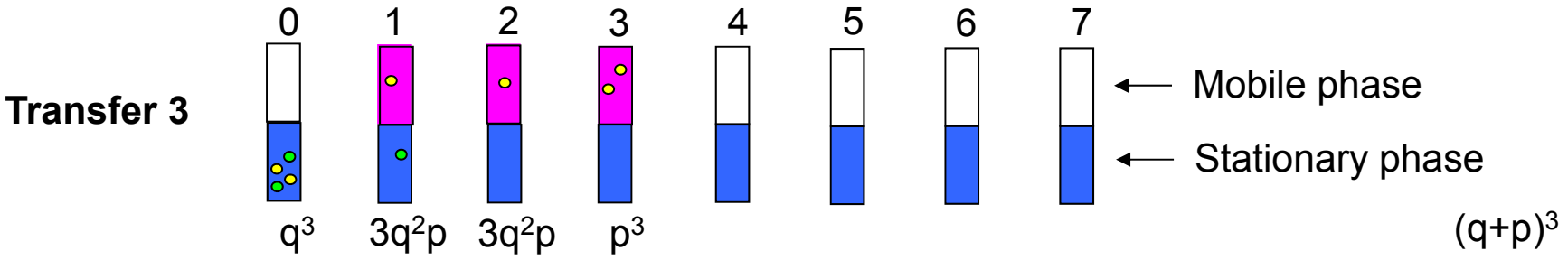
$(q+p)^2 = q^2 + 2\,qp + p^2$

$(q+p)^3 = q^3 + 3\,q^2p + 3qp^2 + p^3$, etc

(9) After given number of transfers (r), the relative amount of A in any tube n is

$$P_{r,n} = \frac{r!}{n!\,(r-n)!}\, p^n\, q^{r-n}$$

Where: $P_{r,n}$ = Fraction of A in tube n after transfer r.



Good news: We can get the distribution of solute among Craig tubes (chromatographic column)

Bad news: give no distribution shape and position.

http://www.chem.uoa.gr/Applets/AppletCraig/Appl_Craig2.html

(10) The binomial can be expended as Gaussian distribution when n larger than 20 (rpq>3).

$$P_{r,n} = \frac{1}{\sqrt{2\pi} * \sqrt{rqp}} \quad \text{Exp } [-(n-rp)^2/2rpq)]$$

Where: $P_{r,n}$ = Fraction of A in tube n after transfer r.

(11) The tube containing the largest amount of A (n_{max}) after r transfer (peak position):

$$n_{max} = rp = r\,[k'/(1 + k')]$$

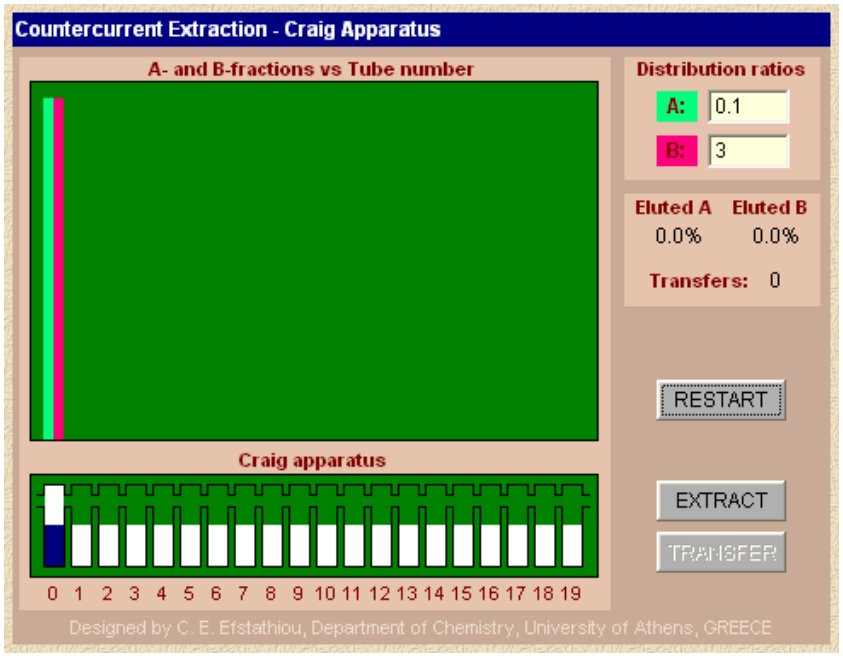
(12) The width of the Gaussian distribution function (peak width) is determined by

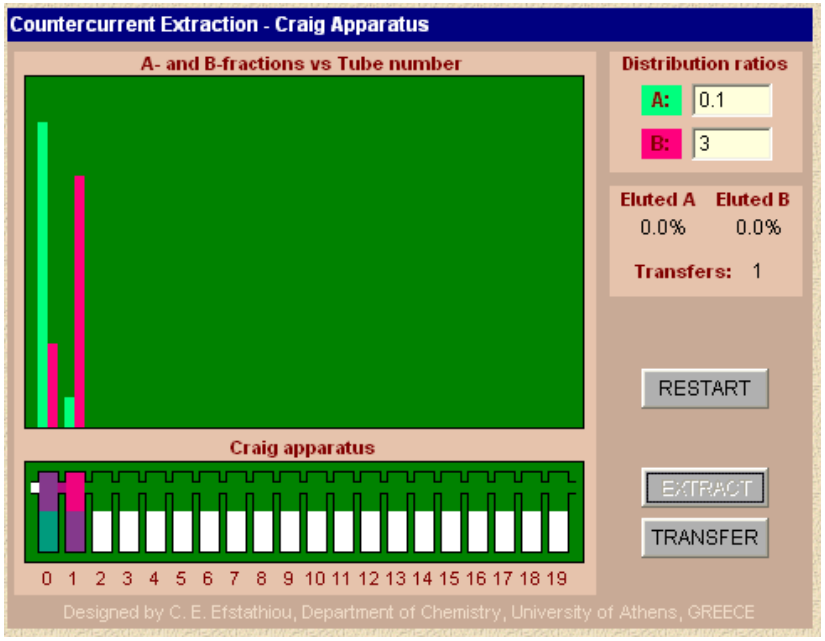
$$\sqrt{rqp} = \sigma = \sqrt{r\,k'/(1+k')^2}$$

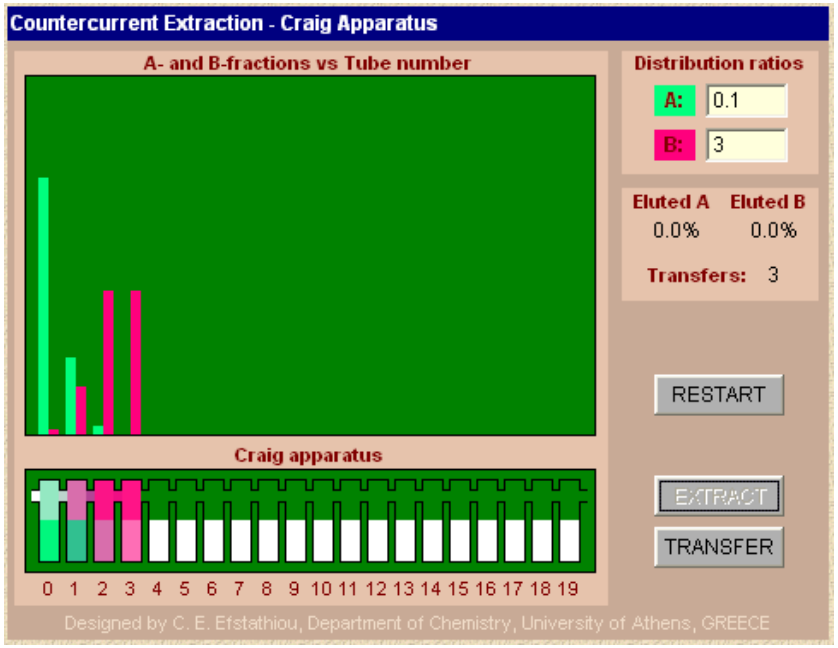
(13) By comparing how the position of a "peak's" maximum and its width change with the number of transfers (or number of equilibria), it becomes clear that the reason that solute become better separated with more transfers is that the distance between their peak maximum is growing faster than their peak widths (i.e. $n_{max} \propto r$, but $\sigma \propto \sqrt{r}$).

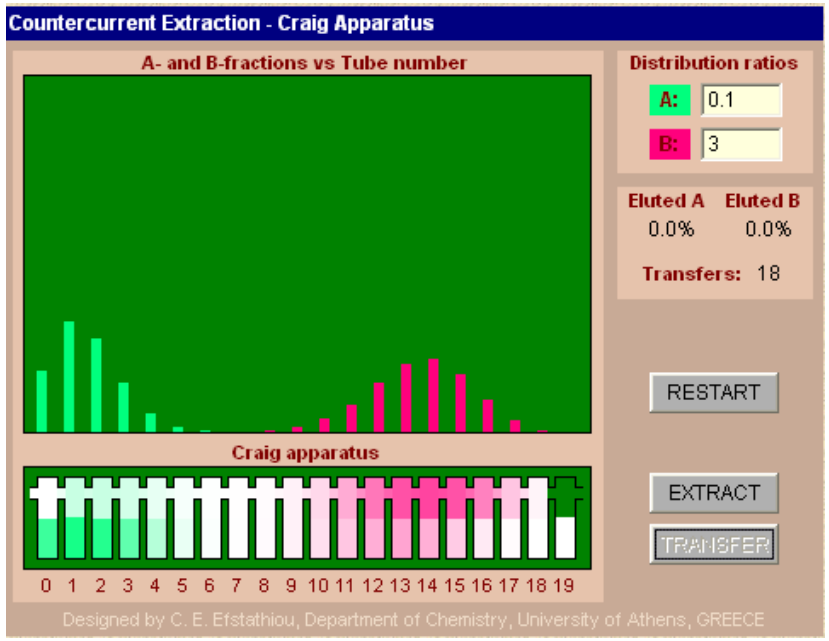
This is the fundamental reason why the Craig apparatus and chromatography can be used to separate compounds.

http://www.chem.uoa.gr/Applets/AppletCraig/Appl_Craig2.html









http://www.chem.uoa.gr/Applets/AppletCraig/Appl_Craig2.html